JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(12), 358–373
https://doi.org/10.12911/22998993/207991
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.05.23
Accepted: 2025.09.01
Published: 2025.10.01

Ecological and human health risk of metal contaminations in an impoundment impacted by wastewater effluents

Smangele Ncayiyana[1], Neo Mashila Maleka[2], Jeffrey Lebepe[1,3*]

[1] School of Life Sciences, University of KwaZulu-Natal, Westville Campus, Durban, South Africa
[2] Department of Human Nutrition and Dietetics, University of Limpopo, Sovenga, South Africa
[3] Department of Biology and Environmental Sciences, Sefako Makgatho Health Sciences University, Pretoria, South Africa
* Corresponding author's e-mail: jlebepe@yahoo.com

ABSTRACT

Wastewater effluents have become a source of metals, particularly in rivers receiving effluents from wastewater treatment plants. The Shongweni Dam is an impoundment on the uMlazi River, which receives the water impacted by wastewater effluents. The dam is bordered by economically disadvantaged communities, which are opting for the inhabitant fish to supplement their protein needs. The present study aimed to investigate the response of fish to contamination and assess health risks that could be associated with the consumption of this fish. The water and sediment showed significant concentrations of metals, with the latter exhibiting a substantially high metal pollution index (MPI). Dry seasons exhibited relatively higher metal contamination indices, suggesting that the reduced water level resulted in high metal concentration. Cu, Mn, Fe, and Pb were the main drivers for high ecological risk on the overall metal contamination. Metals also showed significant concentrations in the muscle of the two fish species, with Cr and Pb exceeding the acceptable level for human consumption. The two species exhibited similar trends with regard to metal dispersion and MPI; however, no significant difference was observed for MPI between species. Nevertheless, Cr and Pb showed THQs of > 1, suggesting possible health implications for consumers, whereas the carcinogenic risk estimation for As, Cd, Cr and Pb showed that consumers remain at risk of cancer. These findings sensitize the communities residing near wastewater-polluted water bodies, particularly the Shongweni Dam, on the possible risk from consuming contaminated fish.

Keywords: uMlazi River, Shongweni Dam, *Oreochromis mossambicus*, *Coptodon rendalli*, chromium, lead.

INTRODUCTION

Metal pollution in aquatic ecosystems has emerged as a global environmental issue due to its ecological and human health impacts (Kumari and Kumar Maiti, 2019). Metal sources could be natural, such as the geology characteristics and volcanic activities, or anthropogenic sources such as agricultural and industrial activities, mining, as well as wastewater treatment works (Sharma et al., 2024; Madhav et al., 2020). In aquatic environments, metals sink to the bottom sediment and transfer back to the water column as the conditions become favorable, e.g. decrease in pH, a change in temperature, or disturbance of the bottom substrates (Zhao et al., 2024). It is therefore imperative to explore the degree of metal contamination in the water bodies that are receiving effluents from anthropogenic activities, to ensure the sustainability and conservation of inhabitant biota. Metals have become a threat to aquatic ecosystems due to their persistence, toxicity, and the capacity to accumulate in aquatic organisms (Saeed et al., 2020). Some metals biomagnify up the food chain, resulting in a lethal dose in top predators (Ali and Khan, 2019).

In aquatic systems, fish are among the top predators, and they can accumulate metals within their organs (Islam et al., 2015a). As a result, fish are regarded as valuable bioindicators of metal contamination of aquatic ecosystems. Despite their importance as bioindicators, fish are regarded as an affordable protein supplement, particularly in communities residing near water bodies. According to Hao et al. (2024), consuming high-quality fish has health benefits, including reduced hypertension, diabetes, and coronary heart diseases, as well as promoting healthy brain development in humans. However, consumption of the fish from a polluted water body can serve as a route of metal exposure to higher predators, such as humans. Metals pose significant health risks to humans, including neurological disorders, renal and reproductive issues, particularly from toxic metals such as antimony (Sb), arsenic (As), cadmium (Cd), and lead (Pb), which are harmful even at low concentrations (Adegbola et al., 2021). Other essential metals, such as iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn), although beneficial in moderate levels, can adversely affect human health when consumed in excess (Zhong et al., 2018). Heath et al. (2004) and Oladimeji et al. (2024) emphasized that metals such as Sb, As, Cd, Cr, Fe, Mn, Pb, selenium (Se), and strontium (Sr) have resulted in the development of fish advisories for the areas impacted by industrial and domestic wastewater effluents. Wastewater effluents are known for their high metal concentration (Berhanu et al., 2024; Mehnaz et al., 2023), making the consumption of the fish from water bodies impacted by wastewater effluents a cause for concern.

Most developing countries are characterized by economically disadvantaged communities, and those residing near rivers often opt for fish for dietary protein. However, the recent pollution trend in these rivers has resulted in uncertainties regarding the safety of consuming fish from potentially contaminated water bodies. The uMlazi River is located in KwaZulu-Natal province in South Africa. The river drains a catchment characterized by negligible agricultural activities and wastewater works. Studies showed that the water bodies receiving effluents from wastewater works are susceptible to metal contamination, which also affects the health of inhabitant biota (Naz et al., 2025; Darko et al., 2016). Despite the Shongweni Dam receiving effluents from a wastewater plant upstream, the metal contamination ecological risk is scarcely explored. Therefore, this study explored metal contamination and assessed ecological risks using relevant indices.

Moreover, the Shongweni Dam is home to numerous fish species, including *Oreochromis mossambicus* and *Coptodon rendalli*, which are preferred by local communities for protein supplements (DWS, 2002). The present study has therefore, aimed to assess the ecological and human health risks associated with metal contamination in the Shongweni Dam, in South Africa. The objectives included: (1) measuring metal concentration in the water and sediment, and quantifying the degree of contamination using different indices, and (2) measuring metal concentrations in the muscle of *O. mossambicus* and *C. rendalli*, and assess their edibility using a US-EPA (2000) desktop protocol. It was hypothesized that sediment would exhibit high metal contamination, with higher concentrations during the dry season. It was also hypothesized that the two fish species would not be safe for human consumption. The findings of the present study provide an insight into the dynamics of metal contamination and behavior in rivers impacted by wastewater effluents, which could be of particular importance for restoration strategies and public health.

MATERIALS AND METHODS

Study area

The Shongweni Dam (29°51’24.984”S, 30°43’19.992”E) is an impoundment on the uMlazi River in KwaZulu-Natal province, South Africa. The dam serves as a repository for contaminants from the upper uMlazi River catchment before the river empties into the Indian Ocean. The catchment is characterized by negligible agricultural activities, and wastewater treatment work (Graham et al., 1998).

Metal analysis

Sampling surveys were conducted during dry (July–August) and wet seasons (November and December) in 2021. Physicochemical parameters, including pH, dissolved oxygen (%), water temperature (°C), total dissolved solids (TDS), and electrical conductivity, were measured at each sampling point, inflow, middle, and dam wall using a HANNA multi-parameter (Model: HI98494). Water samples were also collected at 0.5 m depth using acid-pretreated 1-liter polyethylene bottles at each sampling point, whereas sediment was collected using a Van Veen grab, stored in acid-pretreated 1-liter polyethylene bottles. For both water and sediment, samples were collected in triplicate at each site to form a composite. The samples were stored in a cooler box during transportation and later transferred to a fridge until analysis.

Water and sediment samples were processed and analyzed following the protocol described in Lebepe et al. (2024), Misra et al. (2024), and Hlatshwayo et al. (2024). In brief, the water samples were acidified and filtered through a 0.45 µm membrane, whereas sediment was oven-dried at 110 °C for 48 hours. Approximately 0.2 g of the dried sediment was crushed into a fine powder using a mortar and pestle, then placed in a 200 ml beaker and digested with aqua regia, 3-hydrochloric acid, and 1-nitric acid (3HCL:1NHO_3). The solution was filtered and diluted to 150 ml with distilled water. All chemicals used for sample digestion were of analytical grade supplied by Merck. Metals, i.e., As, Sb, Cd, Cr, Fe, Mn, Pb, Se, and Sr in the water and sediment samples were analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Perkin Elmer, Optima 2100DV). Blank and certified reference materials supplied by Merck were used for quality control. The recovery ranged from 93 to 105% (Figure 1).

Metal pollution indices

Contamination factor

The contamination factor (CF) is the ratio of the metal concentration in sediment to the background concentration, and it was calculated using equation 1 as per Hakanson (1980).

$$CF = \frac{Concentration\ in\ sample}{Background\ concentration} \quad (1)$$

The background concentration from Turekian and Wedepohl (1961) was used. The classification categories described by El-Amier et al. (2017) were used to classify the contamination factor, which ranged from < 1 for low contamination factor to ≥ 6 for very high contamination factor (Appendix A).

Enrichment factor

The enrichment factor is a tool to investigate metal increases in the environment. Metals such as Al and Fe are commonly used as conservation elements, since they are not easily affected by weathering and their concentrations are stable. Therefore, the enrichment is calculated by comparing the concentrations of evaluated metals with those of the conservation elements. In the present study, Fe was used as the conservation metal, and the EF was calculated following Turekian and Wedepohl (1961) using equation 2.

$$EF = \frac{(C_n/C_{Fe})_{sample}}{(B_n/B_{Fe})_{background}} \quad (2)$$

where: C_n – is the concentration of the metal of concern in the sample, C_{Fe} – is the concentration of Fe in the sample, B_n – is the background concentration of the metal of concern, and B_{fe} – is the background concentration of Fe.

The background concentrations used were: *As* = 9.21, Cu = 21, *Fe* = 47200, Pb = 5 (Turekian and Wedepohl, 1961), *Sb* = 8.6 (Dinake et al., 2022), *Mn* = 445 (Franchini et al., 2024), *Sr* = 441 (Zhang et al., 2024). The enrichment factor was classified as per Turekian and Wedepohl (1961) (Appendix A)

Geoaccumulation index

The geoaccumulation index (I_{geo}) determines the pollution level for each metal of interest and is described as the ratio of metal concentration in the sample to the background concentration existing in a natural environment (Turekian and Wedepohl, 1961; Custodio et al., 2024). The index was calculated using equation 3 as per Turekian and Wedepohl (1961).

$$I_{geo} = \log_2\left[\frac{C_n}{1.5B_n}\right] \quad (3)$$

where: C_n – is the concentration of metal in sediment, 1.5 – is the coefficient for minimizing the impact of the background concentration due to lithological variation, B_n – is the background concentration existing in a natural environment.

Muller (1969) classification categories, as described by Addo-Bediako et al. (2021), were used to categorize pollution level, which ranged from 0 for unpolluted to ≥ 5 for extremely polluted (Appendix A).

Pollution load index and degree of contamination

The pollution load index (PLI) determines the extent of sediment pollution by metals and their environmental impact (Custodio et al., 2024).

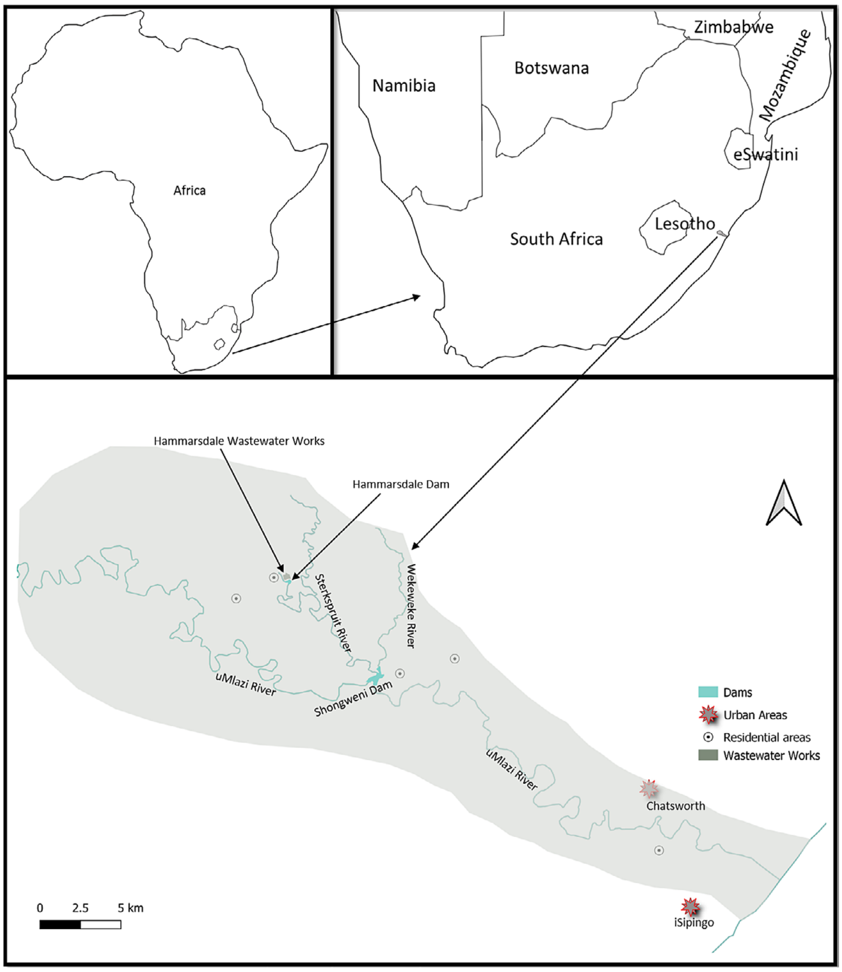

Figure 1. The uMlazi River catchment showing the Shongweni Dam. Credit to QGIS Development Team (2023)

This index was calculated using equation 4 as per Tomlinson et al. (1980).

$$PLI = (CF_1 \times CF_2 \times CF_3 ... CF_n)^{1/n} \quad (4)$$

where: CF_n – is the contamination factor for each metal. The *PLI* of < 1 denotes an unpolluted site, whereas *PLI* >1 denotes a polluted site. The sum of *CF*, which is the contamination degree (C_d) was calculated as per Hakanson (1980) using Equation 5.

$$C_d = \sum_{i=1}^{i=n} Cf \quad (5)$$

where: *CF* – is the contamination factor.

Ecological risk assessment

The potential ecological risk index (RI) is used to assess the overall degree of contamination or ecological risk of metals in sediment. It is described as the sum of ecological risk factors (E_r) for each metal of interest. The E_r is calculated using the toxicity coefficient and CF of each metal (Equation 6). The toxicity coefficients used for this study were 7, 10, 30, 5, 1, 1, 5 and 5 for Sb, As, Cd, Cu, Fe, Mn, Pb and Sr, respectively (Hakanson, 1980; Devanesan et al., 2017; Wang et al., 2018). RI was calculated using Equation 7.

$$E_r^i = T_r^i \times CF_r^i \quad (6)$$

$$Ri = \sum_{i=1}^{n} E_r^i \quad (7)$$

where: T_r is the toxicity coefficient, *CF* is the contamination factor for each metal, E_r is the ecological risk factor for each metal, and *RI* is the potential ecological risk index for the water body.

Fish sampling and processing

Two fish species, *O. mossambicus* (n = 16) and *C. rendalli* (n = 14) were collected from the

Shongweni Dam during dry and wet seasons using an electro-shocker and gill nets. Fish were weighed, their lengths measured and then euthanized as per CCAC (2005) by severing the spinal cord. Fish were opened for health assessment and a muscle sample was cut out, wrapped with foil and stored in dry ice in a cooler box. The muscle sample was later transferred into a fridge and stored until metal analyses.

Metal analysis in fish muscle

Fish muscle was digested following the protocol described in Lebepe et al. (2024), Misra et al. (2024), and Hlatshwayo et al. (2024). In brief, approximately 0.2 g of muscle was oven-dried and digested using an Aqua regia solution ($3HCl:1HNO_3$). The solution was filtered and made to the 100 ml mark using distilled water and kept in the fridge until analysis. Metals, i.e., As, Sb, Cd, Cr, Fe, Mn, Pb, Se, and Sr, were analyzed using ICP-OES. The analysis was carried out with the sediment samples with blanks, and certified reference materials for quality control.

Non-carcinogenic and carcinogenic risk assessment

A risk assessment on human health was carried out by calculating the total hazard quotient (THQ) using the desktop approach developed by the United States Environmental Protection Agency (US-EPA, 2000). This was calculated based on the estimation that an adult weighing 70 kg consumes 0.15 kg of fish muscle portion once per week. For non-carcinogenic risk, THQ was calculated using Equation 8, and Equation 9 was used to calculate carcinogenic cancer (CR) health risks.

$$THQ = \frac{C\times IRF\times EF\times ED}{RfD\times BW\times AT} \quad (8)$$

$$CR = \frac{C \times IRF \times EF \times ED \times OSF}{RfD \times BW \times AT} \quad (9)$$

In the targeted tissue, *C* represents the metal level (mg/kg, ww), *IRF* is the fish consumption rate (150 g), *EF* is the exposure frequency (365 days per year), and *ED* is the duration of exposure (30 years for non-cancer risk). The *RfD* represents the oral reference dose (mg kg/day). The *RfD* levels published by the US-EPA (2013) and Ashraf et al. (2012) were used. *BW* is the body weight (70 kg), and the average time of assessment is abbreviated as *AT* (70 years ·365 days per year). THQ exceeding 1 indicates possible risk, whereas < 1 denotes a minimal or almost negligible human health risk (Heath et al., 2004). The oral slope factor (*OSF*), representing the risk per unit exposure (mg/kg/day), is sourced from the Integrated Risk Information System for carcinogenic metals As (1.5), Cd (15), Cr (0.5), and Pb (8.5×10^{-3}) (US-EPA, 2013).

Carcinogenic risk refers to the likelihood of an individual developing cancer over a lifetime due to exposure to a potential carcinogen (Zhong et al., 2018; Ullah et al., 2017), and the maximum acceptable index range is 10^{-4} and 10^{-6} (US-EPA, 2013).

Data analysis

Statistical analyses were carried out using R-3.1.1 statistical software (R Development Core Team). Normality was tested with a Shapiro-Wilk test, and homogeneity of variance was tested with Levene's test. The Mann-Whitney U test was employed to compare physical parameters and metal concentrations in the water and sediment, as well as health indices between seasons. To assess whether the metal concentrations in the fish muscle varied between fish species and seasons, an independent sample t-test or Mann-Whitney U test was used. Data were statistically significant at $p < 0.05$. Non-metric multidimensional scaling (NMDS) (Clarke and Warwick, 2001) was performed to visualize the metal concentrations in fish muscle from the impoundments and species. Pearson and/or Spearman's correlation test was employed to assess the relationship between fish length and metal accumulation, and inter-metal relationships. The betadisper and Adonis functions in VEGAN were used for multivariate dispersion and analysis (MANOVA) (Anderson 2001a, 2001b).

RESULTS

Metal pollution in sediment and ecological risk assessment

The physical parameters and metal levels in the surface water are presented in Table 1. The pH ranged from neutral to alkaline throughout the study, and no seasonal variation was observed ($p > 0.05$). However, seasonal variations were observed for TDS ($p < 0.05$) and EC ($p < 0.05$), with higher levels being observed during the dry season. Arsenic, Cd, and Cu were generally below detection levels, with notable concentrations being observed for Sb, Fe, Pb, Se, and Sr in the water column (Table1). In contrast, metals exhibited significant concentrations in sediment except for Se, which was below the detection level (Table 1). The mean metal concentration in sediment followed a descending order: Fe > Mn > Cu > Sr > Pb > As > Sb > Cd > Se (Table 1). Moreover, the dry season exhibited higher metal concentrations compared to the wet season. Metal concentrations were relatively low in the water, hence, the MPI of 0.03 was observed compared to 178.57 of the bottom sediment.

Metal contamination indices, EF, CF, and I_{geo} were generally higher during the dry season compared to the wet season (Table 2). Pb, Cu, Mn, and Fe were the main drivers of the contamination indices observed during both seasons. Moreover, the degree of contamination was found to be 18.96 and 14.69 during dry and wet seasons, respectively. Coinciding with the trend observed on the aforementioned indices, RI was found to be higher during the dry season (7779.06), compared to the wet season (1552.99).

Metal concentration in the muscle tissue of the two species

Cadmium was below the detection limit for *O. mossambicus,* whereas a notable concentration was observed for *C. rendalli* (Table 3). No significant differences were observed for Sb ($W = 61.5$, $p > 0.05$), Pb ($W = 118$, $p > 0.05$), Sr ($W = 77.5$, $p > 0.05$), and Se ($W = 72$, $p > 0.05$) between species. However, Fe ($W = 177$, $p < 0.05$) and Cr ($W = 210$, $p < 0.05$) showed a significant difference

Table 1. Physical parameters and metal concentrations (mean ± stdev) observed in the water and sediment during dry and wet seasons in 2021. Water SI units are in mg/l unless specified otherwise, whereas sediment is in mg/kg dw

Parameter	Surface water		
	Dry	Wet	Guidelines
Temperature (℃)	19.42±0.88	20.28±0.18	-
DO (%)	63.07±9.03	56.63±6.25	-
pH	7.91±0.22	8.19±0.14	6.0–9.0 CCME (2012)
TDS	287.67±11.55	166.00±4.36	1000 Scannell and Jacobs (2001)
EC (µS/cm)	572.33±19.63	337±1	-
Antimony	0.001	0.001	-
Arsenic	<0.001	0.001	0.005 CCME (2012)
Cadmium	<0.001	<0.001	0.0004 DWAF (1996)
Copper	<0.010	<0.010	0.0014 DWAF (1996)
Iron	**1.33**	0.15	0.3 CCME (2012)
Lead	**0.108**	**0.07**	0.00012 DWAF (1996)
Manganese	0.097	<0.025	0.18 DWAF (1996)
Selenium	**0.005**	**0.002**	0.001 CCME (2012)
Strontium	0.076	0.07	-
Sediment			
Antimony	9.33±1.85	0.733±0.46	-
Arsenic	**19.67±3.21**	**10.4±8.21**	5.9 CCME (2001)
Cadmium	**1**	<0.001	0.6 CCME (2001)
Copper	**470±177.39**	**185.6±138.24**	37.5 CCME (2001)
Iron	171000±28.59	99733.33±62.14	-
Manganese	**5333±71.59**	**2805.67±58.16**	300 Onjefu et al. (2016)
Lead	**151±40.58**	**72±56.15**	35 MacDonald et al. (2000)
Selenium	<0.001	<0.001	-
Strontium	204±85.66	88.2±65.48	-

Note: Bold = exceeded the guidelines.

Table 2. Metal contamination indices observed during dry and wet seasons in the Shongweni Dam in 2021

Metals	Enrichment factor		Contamination factor		Geoaccumulation index	
	Dry	Wet	Dry	Wet	Dry	Wet
Antimony	0.28	0.04	1.01	0.09	-0.59	-4.29
Arsenic	0.59	0.53	2.12	1.13	0.49	-0.67
Cadmium	0.01	-	0.02	-	-5.50	-
Copper	6.18	4.18	22.40	8.84	3.84	2.44
Fe	1.00	1.00	3.62	2.11	1.27	0.49
Manganese	3.31	2.98	11.98	6.30	3.00	2.07
Lead	8.36	6.78	30.30	14.33	4.30	3.25
Strontium	0.23	0.17	0.85	0.37	-0.91	-2.30

between species, with *C. rendalli* exhibiting relatively higher concentrations (Table 3). Arsenic showed no significant difference between species (W = 100, $p > 0.05$), whereas a significant difference was observed for Mn between species (W = 30, $p < 0.05$), with *C. rendalli* exhibiting higher concentrations (Table 3). Nevertheless, non-metric multidimensional scaling showed a clear separation between species (MANOVA, $p < 0.001$) (Figure 2). Moreover, dispersion results showed a significant difference (Permidisp, $p < 0.05$) with average distances to median being 0.91 for *C. rendalli* and 0.65 for *O. mossambicus*. The metal pollution index exhibited a notable value for both species. However, no significant difference was observed for MPI between species ($t = 1.08$, $p > 0.05$), with a mean of 1.55 and 1.81 being observed for *C. rendalli* and *O. mossambicus*, respectively. Moreover, fish size showed a poor association with the MPI ($r = -0.17$, $p > 0.05$).

Non-carcinogenic and carcinogenic risk assessment

The non-carcinogenic THQs are presented in Table 4. Chromium and Pb exhibited THQs of > 1 for both populations (Table 4). *Coptodon rendalli* mean THQs followed a descending order: Pb > Cr > As > Sb > Fe > Se > Mn > Sr > Cd, whereas *O. mossambicus* exhibited: Pb > Cr > As > Sb > Fe > Se > Sr > Mn > Cd. Chromium and Pb showed THQ > 1 for 100% of the sampled *C. rendalli* and *O. mossambicus* populations, whereas As exhibited THQ > 0.5 for both species (Table 3). Worth noting are the Sb and Fe, which have exhibited THQs of 0.2 for both species. Carcinogenic risk assessment was carried out for As, Cd, Cr, and Pb, as the slope factor is not readily available for other metals. The CR for *O. mossambicus* were 7.84×10^{-1}, 9.95×10^{-1}, 1.47×10^{-1}, and 0 for As, Cr, Pb, and Cd, respectively, whereas *C. rendalli* e×hibited the CR values of 8.89×10^{-1} for As, 3.87×10^{-3} for Cd, 1.55×10^{-1} for Cr, and 5.59×10^{-1} for Pb.

DISCUSSION

Metal contamination and ecological risk assessment

Physical water parameters are known to influence the dynamics of chemical contaminants in aquatic ecosystems. The pH is known to be the key driver of metal bioavailability in freshwater environments. Moreover, TDS correlates positively with EC, which also affects the water pH (Islam et al., 2017). In the present study, the pH was within the CCME (2012) guideline for aquatic ecosystems. The pH can be influenced by biological activities, geology, and runoffs from the Earth's surface (Omarjee et al., 2021). Nevertheless, the anthropogenic activities in the uMlazi River catchment have not significantly affected the water pH.

Table 4. Target hazard quotient for trace metals found in the muscle tissue of *Coptodon rendalli* and *Oreochromis mossambicus* from the Shongweni Dam in 2021

Metals	*C. rendalli*	*O. mossambicus*
Sb	0.483±0.318	0.262±0.298
As	0.592±0.180	0.522±0.225
Cd	-	-
Cr	11.900±2.457	1.990±0.576
Fe	0.257±0.065	0.194±0.034
Mn	0.022±0.021	0.005±0.009
Pb	18.332±4.103	17.263±4.116
Se	0.076±0.042	0.142±0.114
Sr	0.009±0.005	0.011±0.002

Table 3. Metal concentrations (mg/kg dry wt; mean ± standard deviation) in the tilapia fish species collected from the Shongweni Dam in 2021 and the permissible limits

Metals	*C. rendalli*	*O. mossambicus*	Permissible limits
Sb	0.139±0.046	0.114±0.038	1.5 (FAO, 1983)
As	0.104±0.009	0.100±0.007	2 (JECFA, 2002)
Cd	0.002±0.001	ND	0.17 (FAO, 1983)
Cr	**19.756±4.059**	**3.250±0.941**	2 (MOHSAC, 2006)
Fe	98.145±23.924	73.921±12.941	333.30 (Mokhtar et al., 2009)
Mn	**2.899±0.899**	**1.435±0.433**	3.52 (IAEA, 2003)
Pb	**0.538±0.163**	**0.536±0.128**	0.02 (FAO, 2003)
Se	0.208±0.120	0.386±0.311	1 (MOHSAC, 2006)
Sr	2.654±1.687	3.479±0.703	-

Note: ND: not detected, Bold: concentrations exceeding the guidelines.

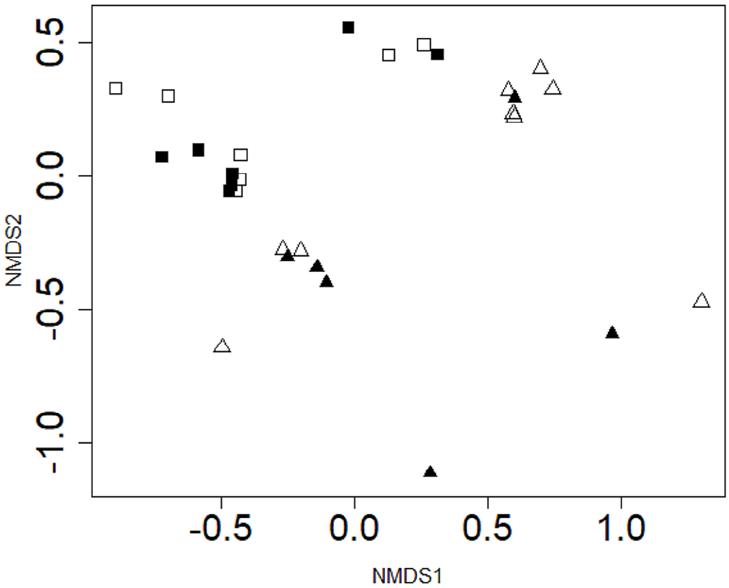

Figure 2. Non-metric multidimensional scaling presenting metal concentrations with seasons and between species (*Oreochromis mossambicus*, low flow (γ) and high flow (■); *Coptodon rendalli* (Δ) and high flow (▲)

Similarly, TDS was also within Scannell and Jacobs (2001) guideline, whereas EC was within the USEPA (2025) range of 150–500 µS/cm, which optimally supports freshwater ecosystems. The runoffs and wastewater effluents are some of the key drivers of TDS and EC in aquatic ecosystems (Rameshkumar et al., 2019), However, the water from Shongweni Dam has not suffered a significant impact with regard to TDS and EC.

In contrast, metals exhibited notable concentration in the water column except for As, Cd, and Cu. Moreover, Fe and Pb in the water exceeded CCME (2012) and DWAF (1996) guidelines for aquatic ecosystems. However, relatively higher concentrations were observed in the sediment, except for Se, which was below the detection level. Arsenic, Cu, Mn and Pb in sediment exceeded the guidelines (Table 1) for aquatic ecosystems (CCME, 2001; Onjefu et al., 2016; MacDonald et al., 2000). Moreover, Mn showed moderate, whereas Cu, and Pb exhibited significant enrichment factor as per Barbieri (2016) (Appendix A). Similarly, Cu, Mn and Pb showed a CF > 6, which signifies a very high contamination, whereas Sb, As, and Fe showed moderate contamination as per Weissmannová and Pavlovský (2017). Cu, Mn and Pb I_{geo} showed moderately to heavily contaminated, whereas MPI was > 1 for both dry (3.32) and wet (1.66) seasons. The concentrations of Cu, Mn, and Pb are showing to be a cause for concern in this dam, and the risks seem to be high during the dry season. The contamination degree has exhibited a very high to extremely high contamination, whereas the RI was very high (Liao et al., 2022).

The observed contamination indices and RI were higher than those observed in urban riverine sediment (Zheng et al., 2024) and in a river impacted by industrial activities (Kolawole Tesleem et al., 2018). According to Wang et al. (2018), metal threat could be influenced by its behavior and affinity to the receiving end. Therefore, different metals may have different effects even when they occur in similar concentrations.

In aquatic ecosystems, metals may sink to the bottom sediment or remain dissolved in the water column depending on factors such as pH, salinity, temperature, etc. (Custodio et al., 2024). In alkaline pH, metals tend to precipitate and sink to the bottom sediment (Zhao et al., 2024), hence, high concentrations in sediment are expected in alkaline pH waters. According to Rzetala (2015), the ability of the sediment to adsorb metals makes it a potential source of metals even in the situations where the discharge of effluents has stopped. In the present study, the RI of metal contamination is extremely high, which compromises its potential to provide ecosystem services such as water for drinking and fish for consumption to local communities.

Metal concentrations in fish

Fish inhabiting metal-contaminated water bodies were found to accumulate metals within their tissues. The dynamics of bioaccumulation are governed by factors such as pH, salinity, temperature, the chemical properties of metals, and of particular interest, species and feeding habits (Khan et al., 2023; Yi and Zhang, 2012). In the present study, the two species occupy the same trophic level, and their potential to accumulate metals is likely to be the same. The two species showed notable concentrations of Sb, Fe, Cr, As, Pb, Cd, Mn, Se, and Sr, with Cr, Fe, and Mn even showing a significant difference between the two species (Table 2).

Sb, As, and Cd were below the FAO (1983), MOHSAC (2006), and FAO (1983) permissible limits, respectively, for both species (Table 2). The Sb concentrations observed for both species corroborate those reported by Lebepe et al. (2024) and are lower than those reported by Jooste et al. (2015) in polluted water bodies, whereas As concentrations observed corroborated those reported at the Inanda and Nagle Dam populations (Misra et al., 2024). Moreover, the As concentrations observed in the present study were relatively lower than those reported for freshwater fish from the Olifants River and Mohammadpur Dam (Ullah et al., 2017; Addo-Bediako et al., 2014; Lynch et al., 2016a). Cd concentration was below the detection level for *O. mossambicus,* whereas a notable concentration was recorded for *C. rendalli*. The Cd concentration for *C. rendalli* was comparable to those observed in freshwater fish from polluted water bodies (Adegbola et al., 2021; Mannzhi et al., 2021). In contrast, Cd concentration in *C. rendalli* was lower than that observed for *C. gariepinus* and higher than that observed for *O. mossambicus* reported by Ullah et al. (2017).

Coinciding the Cd trend, Cr exhibited relatively higher concentrations for *C. rendalli* compared to *O. mossambicus.* However, both species exhibited concentrations exceeding the WHO (2005) and MOHSAC (2006) permissible limit of 1 mg/kg and 2 mg/kg, respectively. The Cr concentrations reported in the current study corroborated those reported for *L. rohita* in the Buriganga River (Ahmed et al., 2016) and were significantly higher than those reported at the Karwan Bazar (Ullah et al., 2017) and the Luvuvhu River (Mannzhi et al., 2021). In contrast, the current Cr concentrations were significantly lower than those reported by Addo-Bediako et al. (2014). Contrasting the Cr trend, Fe exhibited a concentration within the permissible limit of 333.30 mg/kg (JECFA, 2002) for both species. The observed Fe levels were significantly higher than those reported for tilapia species at the Albasini Dam (Nibamureke et al., 2016), Flag Boshielo (Lynch et al., 2016b), and the Luvuvhu River (Mannzhi et al., 2021), but relatively lower than those reported by Addo-Bediako et al. (2014). Manganese has also shown concentrations below the 3.52 mg/kg permissible limit (IAEA, 2003) and exceeding the FAO (2003) limit of 2 mg/kg for both species. Manganese concentrations were comparable to those observed for *Cyprinus carpio* from the Masinga Dam and *Sarotherodon melanotheron* from the Ogun River (Adegbola et al., 2021; Nzeve and Kitur, 2019). Contrastingly, Mn concentrations were notably lower than those reported for other freshwater fish (Mannzhi et al., 2021; Nibamureke et al., 2016; Lynch et al., 2016b).

Lead is a toxic metal that has been regarded as a cause for concern in most freshwater bodies. In the present study, Pb exceeded the regulatory safe threshold of 0.2 mg/kg (FAO, 2003) and 0.5 mg/kg (MHSAC, 2006) for fish consumption for both tilapia species. However, Pb concentrations were lower than those reported by other related studies (Jooste et al., 2015; Naangmenyele et al., 2021) for both species, and comparable to those observed by Hossain et al. (2023) and Kotacho et al. (2024). In contrast, the Pb concentration was higher than that observed by Yin et al. (2024) and Blankson et al. (2024) in the fish from contaminated water bodies. Selenium is known to have antagonistic interactions with most metals due to its role as an essential metal (Barone et al., 2021). In the present study, Se was within the MOHSAC (2006) limit of 1 mg/kg for both species. The Se concentration was comparable to that observed by Misra et al. (2024) and lower than that reported by Li et al. (2024) in fish from polluted water bodies. Another metal that received less attention in aquatic environments is Sr, which is known for its close association with calcium. There is no permissible limit found in the literature for Sr due to its low toxicity in aquatic environments (McPherson et al., 2014). However, Sr concentrations observed in the present study were higher than those observed by Ullah et al. (2017) and Lebepe et al. (2020) in the muscle of fish from polluted water bodies.

The variability in metal bioaccumulation among both tilapia species reflects intrinsic physiological differences and external environmental drivers. Organs such as muscle are not target sites for metals due to their distinct metabolic role in storage and biotransformation (Monferran et al., 2016). However, elevated concentrations, which were generally similar, were observed for both species. According to Maurya and Malik (2018), species occupying the same trophic levels tend to accumulate the same metal concentrations. However, factors such as fish size and age may influence the accumulation. In addition, physicochemical parameters such as water temperature, salinity, and pH are possible drivers of metal accumulation in fish (Hossain et al., 2023). Metal pollution index in fish muscle was also higher than that observed in the water column and lower than that reported in the sediment. The trend suggests that sediment will continue to be a threat to the edibility of fish at the Shongweni Dam. Moreover, the Shongweni Dam continues to receive effluents from wastewater works and agricultural runoffs, which enhance the influx of metals and have the potential to influence the pH and salinity, which enhances metal toxicity. Therefore, the high metal concentrations in fish and sediment are becoming a cause for concern, particularly since the dam is used for artisanal fisheries.

Health risk assessment

The fish from contaminated water bodies tend to accumulate metals exceeding levels for human consumption. Non-carcinogenic risk assessment has been used as a tool to determine fish edibility and categorize groups susceptible to health implications. In the present study, Cr and Pb exhibited THQ > 1 for both species. Moreover, As showed a THQ > 0.5 whereas Sb exhibited THQ > 0.29. Although the THQs for As and Sb are < 1, these metals can still have health implications should the fish be consumed by a child or sensitive individuals. The THQ for Cr was also observed by Hao et al. (2024), Lebepe et al. (2024) and Hao et al. (2024). Moreover, Hlatshwayo et al. (2024) reported THQ > 1 for *C. rendalli* in the uMgeni River system impacted by metallurgic industrial activities. In contrast, Darko et al. (2016), Sara et al. (2017) and Huang et al. (2019) observed THQ < 1 for Cr in fish from wastewater effluent-contaminated water bodies.

The lead concentrations in fish have been a cause for concern in most countries. In South Africa, Hlatshwayo et al. (2024) reported the Pb THQ > 1 in the uMgeni River system receiving effluents from wastewater works and industrial areas, whereas Biswas et al. (2023) observed the THQ > 1 in the fish from a river impacted by industrial activities in Bangladesh. Moreover, Naz et al. (2025) reported Pb THQ > 1 in the fish from a river impacted by agricultural runoffs and wastewaters from industrial effluents in Pakistan. The concerning Pb THQs were also recorded in the fish from polluted water bodies in Morocco (Kotacho et al., 2024), Nigeria (Ezemonye et al., 2019), Kenya (Esilaba et al., 2020), India (Kumari and Kumar Maiti, 2019), Taiwan (Vu et al., 2017) and China (Noman et al., 2022). However, Mehnaz et al. (2023), Berhanu et al. (2024) and Darko et al. (2016) exhibited the Pb THQ < 1 in fish from a river contaminated by wastewater effluents. Moreover, Roy et al. (2021) reported Pb THQ < 1 for *Oreochromis niloticus* cultured in a wastewater treatment plant pond. It is evident that wastewater effluents are not entirely the primary contributor of Pb in most aquatic ecosystems. However, metal content in wastewater effluents also depends on the land use and other anthropogenic activities that release effluents into the wastewater plants.

Other metals, such as As and Sb, showed THQs < 1, suggesting the absence of health implications. However, the assessment was made based on assumptions that a 150g portion is consumed by a 70 kg adult. Therefore, THQs > 0.5 could also be a cause for concern for children, or if the consumption rate increases. Arsenic THQs were comparable to those observed by Zhong et al. (2018) and Hao et al. (2024) on the fish from water bodies impacted by wastewater effluents and agricultural activities. Moreover, Mehnaz et al. (2023) reported concentration below the detection level in the fish from wastewater-polluted water bodies. On the other hand, Islam et al. (2015b) reported THQ > 1 in the fish from an urban river receiving effluents from wastewater works. Moreover, Vu et al. (2017) observed THQ > 1 in the fish from a river receiving effluents from wastewater works and urban runoffs. Wastewater effluents seem to be one of the contributors of As in aquatic environments, and this is concerning for the rivers draining urbanized catchments and those serving as a repository for effluents from remote wastewater works.

Despite Cr and Pb being the only metals exhibiting non-carcinogenic health risk, and As and Sb being on the verge of exceeding the threshold THQ value of 1, the carcinogenic risks exceeded the threshold of × 10^{-4} for As, Cd, Cr and Pb for both species. Most studies showed low non-carcinogenic risk and high carcinogenic risks in fish from wastewater-polluted water bodies (Mehnaz et al., 2023; Biswas et al., 2023). Although eating fish is regarded as beneficial for human health, *C. rendalli* and *O. mossambicus* from the Shongweni Dam seem to be unsafe for long-term consumption.

CONCLUSIONS

The As, Cd, Cu, Mn, and Pb concentrations in sediment exceeded the guidelines for aquatic ecosystems. Moreover, metal concentration in sediment was extremely high, such that the risk index was > 1000, with dry season being > 7000. Cu, Mn, and Pb were the metals of concern, whereas Sb, As, and Fe were on the verge of becoming hazardous in sediment. Moreover, the ecological risk of metal contamination is relatively high during dry seasons, possibly due to reduced hydrologic regime. Similarly, fish showed increased metal concentrations, with Cr, Mn, and Pb exceeding the permissible limit for human consumption. Moreover, the non-carcinogenic risks were > 1 for Cr and Pb, with the THQ of Cr being relatively higher for *C. rendalli* compared to *O. mossambicus*. As and Sb were on the verge of exceeding the threshold of 1, with *C. rendalli* exhibiting a relatively higher THQ compared to *O. mossambicus*. However, the carcinogenic risks for As, Cd, Cr, and Pb exceeded the threshold of × 10^{-4} for both species. It is recommended that future studies look at the dynamics governing metal transfer between sediment and the water, and the seasonality of the transfers to allow a comprehensive prediction of the fate of these metals under different conditions, and fish as potential destination.

Acknowledgments

The authors would like to acknowledge the University of KwaZulu-Natal for technical support and the Shongweni Dam Nature Reserve team for unlimited access to their premises. Special thanks to postgraduate students for their assistance during fieldwork and the Department of Biology and Environmental Sciences of the Sefako Makgatho Health Sciences University for the financial support granted to cover the publication fees of this research article.

This research was funded by the National Research Foundation of South Africa (Grant no. 121848). The animal study protocol was approved by the University of KwaZulu-Natal Animal Research Ethics Committee (Ref: AREC/019/018).

REFERENCES

1. Kumari, P., Kumar Maiti, S. (2019). Health risk assessment of lead, mercury, and other metal (loid) s: A potential threat to the population consuming fish inhabiting, a lentic ecosystem in Steel City (Jamshedpur), India. *Human and Ecological Risk Assessment: An International Journal*, 1–19.
2. Sharma, A.K., Sharma, M., Sharma, S., Malik, D.S., Sharma, M., Sharma, A.K. (2024). A systematic review on assessment of heavy metals toxicity in freshwater fish species: current scenario and remedial approaches. *Journal of Geochemical Exploration*, 107472.
3. Madhav, S., Ahamad, A., Singh, A.K., Kushawaha, J., Chauhan, J.S., Sharma, S., Singh, P. (2020). Water pollutants: sources and impact on the environment

and human health. *Sensors in water pollutants monitoring: Role of material*, 43–62.

4. Zhao, S., Zhao, Y., Cui, Z., Zhang, H., Zhang, J. (2024). Effect of pH, temperature, and salinity levels on heavy metal fraction in lake sediments. *Toxics*, *12*(7), 494.
5. Saeed, F., Iqbal, K., Atique, U., Javid, A., Khan, N., Iqbal, S., Majeed, H., Azmat, H., Khan, B., Baboo, I. (2020). Toxic trace metals assessment in selected organs of edible fish species, sediment and water in Head Punjnad, Punjab, Pakistan. *Punjab University Journal of Zoology*, *35*(1), 43–50.
6. Ali, H., Khan, E. (2019). Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs – Concepts and implications for wildlife and human health. *Human and Ecological Risk Assessment: An International Journal*, *25*(6), 1353-1376. https://doi.org/10.1080/10807039.2018.1469398
7. Islam, M.S., Ahmed, M.K., Raknuzzaman, M., Habibullah-Al-Mamun, M., Masunaga, S. (2015a). Metal speciation in sediment and their bioaccumulation in fish species of three urban rivers in Bangladesh. *Archives of Environmental Contamination and Toxicology*, *68*(1), 92–106.
8. Hao, Y., Wei, X., Zhao, X., Zhang, X., Cai, J., Song, Z., Liao, X., Chen, X., Miao, X. (2024). Bioaccumulation, contamination and health risks of trace elements in wild fish in Chongqing City, China: a consumer guidance regarding fish size. *Environmental Geochemistry and Health*, *46*(11), 467. https://doi.org/10.1007/s10653-024-02219-5
9. Adegbola, I.P., Aborisade, B.A., Adetutu, A. (2021). Health risk assessment and heavy metal accumulation in fish species (*Clarias gariepinus* and *Sarotherodon melanotheron*) from industrially polluted Ogun and Eleyele Rivers, Nigeria. *Toxicol Rep*, *8,* 1445–1460. https://doi.org/10.1016/j.toxrep.2021.07.007
10. Zhong, W., Zhang, Y., Wu, Z., Yang, R., Chen, X., Yang, J., Zhu, L. (2018). Health risk assessment of heavy metals in freshwater fish in the central and eastern North China. *Ecotoxicology and Environmental Safety*, *157,* 343–349. https://doi.org/10.1016/j.ecoenv.2018.03.048
11. Heath, R., Du Preez, H., Genthe, B., Avenant-Oldewage, A. *Freshwater Fish and Human Health Reference Guide*; WRC Report No TT213/04. Water Research Commission, Pretoria: 2004.
12. Oladimeji, T.E., Oyedemi, M., Emetere, M.E., Agboola, O., Adeoye, J.B., Odunlami, O.A. (2024). Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon*, *10*(23), e40370. https://doi.org/10.1016/j.heliyon.2024.e40370
13. Berhanu, G., Lemma, H., Mekonnen, S., Dadi, D. (2024). Heavy metals in wastewater and fish collected from waste stabilization pond and human health risks in southwestern Ethiopia. *Frontiers in Environmental Health*, *3.* https://doi.org/10.3389/fenvh.2024.1386827
14. Mehnaz, M., Jolly, Y.N., Alam, A.K.M.R., Kabir, J., Akter, S., Mamun, K.M., Rahman, A., Islam, M.M. (2023). Prediction of hazardous effect of heavy metals of point-source wastewater on fish (*Anabas cobojius*) and human health. *Biological Trace Element Research*, *201*(6), 3031–3049. https://doi.org/10.1007/s12011-022-03378-1
15. Naz, S., Ullah, Q., Fouad, D., Qadeer, A., Lateef, M., Hassan, M.W., Chatha, A.M.M. (2025). Trace elements in fish species from the Punjnad headworks: Bioaccumulation and human health risk assessment. *PLOS ONE*, *20*(1), e0310744. https://doi.org/10.1371/journal.pone.0310744
16. Darko, G., Azanu, D., Logo, N.K. (2016). Accumulation of toxic metals in fish raised from sewage-fed aquaculture and estimated health risks associated with their consumption. *Cogent Environmental Science*, *2*(1), 1190116.
17. DWS. *State of rivers report: uMngeni River and neighbouring rivers and streams. WRC Report No.TT 200/02. Water Research Commission, Pretoria*; 2002.
18. US-EPA. *Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories*; Report No. EPA-823-B-00-008, Diane Publishing, Washington DC., 2000; 156.
19. Graham, P.M., Dickens, C.W.S., Mbowa, S. *Modelling the water quality in impoundments within the Umgeni Water operational area and the consequences for potable water treatment costs. WRC Report No 615/1/98. Water Research Commission, Pretoria*; 186845410X; 1998.
20. Lebepe, J., Selala, M.C., Takai, Y., Maleka, N.M., Hlatshwayo, S.B.S. (2024). Accumulation of heavy metals in tissues of *Oreochromis Mossambicus* from the uMgeni River and human health risk assessment. *Water, Air & Soil Pollution*, *235*(11), 726. https://doi.org/10.1007/s11270-024-07553-z
21. Misra, A., Bissessur, A., Selala, M.C., Lebepe, J. (2024). Accumulation and health implications of arsenic, mercury, and selenium in selected freshwater fish species in the uMgeni River, South Africa. *Environmental Pollutants and Bioavailability*, *36*(1), 2296973. https://doi.org/10.1080/26395940.2023.2296973
22. Hlatshwayo, S.S.B., Bissessur, A., Selala, M.C., Takai, Y., Lebepe, J. (2024). Metal distribution in three organs and edibility assessment on Coptodon rendalli from the Umgeni River impacted by metallurgic industrial activities. *Environmental*

Monitoring and Assessment, *196*(8), 742. https://doi.org/10.1007/s10661-024-12875-w

23. Team, Q.D. *QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org*; 2023.
24. Turekian, K.K., Wedepohl, K.H. (1961). Distribution of the elements in some major units of the earth's crust. *Geological society of America bulletin*, *72*(2), 175–192.
25. El-Amier, Y.A., Elnaggar, A.A., El-Alfy, M.A. (2017). Evaluation and mapping spatial distribution of bottom sediment heavy metal contamination in Burullus Lake, Egypt. *Egyptian Journal of Basic and Applied Sciences*, *4*(1), 55-66. https://doi.org/10.1016/j.ejbas.2016.09.005
26. Dinake, P., Mokgosi, S.M., Kelebemang, R., Kereeditse, T.T., Motswetla, O. (2022). Pollution assessment of antimony in shooting range soils. *South African Journal of Chemistry*, *76*72, 72–78. https://doi.org/10.17159/0379-4350/2022/v76a1
27. Franchini, S., Barbieri, M., D'Amato, E., Sappa, G. (2024). An assessment of high natural manganese concentration in the groundwater upstream of a non-hazardous solid waste plant in the Southern Latium Region. *Water 16*, doi:https://doi.org/10.3390/w16202939.
28. Zhang, S., Li, Q., Zou, Y., Liu, B., Yang, J., Zheng, H., Liu, G. (2024). Using isotopic lead and strontium in sediments to trace natural and anthropogenic sources in the Bohai Sea. *Scientific Reports*, *14*(1), 30267. 10.1038/s41598-024-81493-w
29. Custodio, M., Fow, A., De la Cruz, H., Chanamé, F., Huarcaya, J. (2024). Potential ecological risk from heavy metals in surface sediment of lotic systems in central region Peru. *Frontiers in Water*, *Volume 5,* 2023. https://doi.org/10.3389/frwa.2023.1295712
30. Muller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. *GeoJournal*, *2* 108–118.
31. Addo-Bediako, A., Nukeri, S., Kekana, M. (2021). Heavy metal and metalloid contamination in the sediments of the Spekboom River, South Africa. *Applied Water Science*, *11*(7), 133. https://doi.org/10.1007/s13201-021-01464-8
32. Tomlinson, D.L., Wilson, J.G., Harris, C., Jeffrey, D. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen*, *33,* 566–575.
33. Hakanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research*, *14*(8), 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8
34. Devanesan, E., Gandhi, M.S., Selvapandiyan, M., Senthilkumar, G., Ravisankar, R. (2017). Heavy metal and potential ecological risk assessment in sedimentscollected from Poombuhar to Karaikal Coast of Tamilnadu using Energy dispersive X-ray fluorescence (EDXRF) technique. *Beni-Suef University Journal of Basic and Applied Sciences*, *6*(3), 285–292. https://doi.org/10.1016/j.bjbas.2017.04.011
35. Wang, N., Wang, A., Kong, L., He, M. (2018). Calculation and application of Sb toxicity coefficient for potential ecological risk assessment. *Science of the Total Environment*, *610–611,* 167–174. https://doi.org/10.1016/j.scitotenv.2017.07.268
36. CCAC. (2005). Canadian Council on Animal Care (CCAC) guidelines on the care and use of fish in research, teaching and testing.
37. US-EPA. *Integrated Risk Information System (IRIS). United States Environmental Protection Agency, Environmental Criteria and Assessment Office*; http://www.epa.gov/IRIS/ Accessed July 2015, Cincinnati, OH., 2013.
38. Ashraf, M., Maah, M., Yusoff, I. (2012). Bioaccumulation of heavy metals in fish species collected from former tin mining catchment. *International Journal of Environmental Research*, *6*(1), 209–218.
39. Ullah, A.K.M.A., Maksud, M.A., Khan, S.R., Lutfa, L.N., Quraishi, S.B. (2017). Dietary intake of heavy metals from eight highly consumed species of cultured fish and possible human health risk implications in Bangladesh. *Toxicology Reports*, *4,* 574–579. https://doi.org/10.1016/j.toxrep.2017.10.002
40. CCME. (2012). *Canadian water quality guidelines for the protection of aquatic life. Introduction*; Canadian environmental quality guidelines, Canada. Accessed on the 09 September 2019. http://st-ts.ccme.ca/en/index.html, 1–13.
41. Scannell, P., Jacobs, L. (2001). *Effects of Total Dissolved Solids On Aquatic Organisms: A review. Technical Report No. 1-6. Alaska Department of Fish and Game, The Division of Habitat and Restoration. Washington DC.*
42. DWAF. (1996). *South African Water Quality Guideline*; 7, Aquatic Ecosystem, 2nd Edition, Pretoria.
43. CCME. *Canadian sediment quality guidelines for the protection of aquatic life* https://www.elaw.org/system/files/sediment_summary_table.pdf, accessed on the 25th January 2018., 2001.
44. Onjefu, S.A., Kgabi, N., Taole, S. (2016). Heavy metal seasonal distribution in shore sediment samples along the coastline of Erongo Region, western Namibia. *European Journal of Scientific Research*, *139*(1), 49–63.
45. MacDonald, D.D., Ingersoll, C.G., Berger, T. (2000). Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Archives of Environmental Contamination and Toxicology*, *39*(1), 20–31.

46. FAO. *Complation of legal limits for hazardous substances in fish and fishery products*; FAO Fisheries Circular No. 764. Rome, 1983.
47. JECFA. *Limit test for heavy metals in food additive specifications*; FAO/WHO expert committee on food additives. http://www.fao.org/fileadmin/templates/agns/pdf/jecfa/2002-09-10_Explanatory_note_Heavy_Metals.pdf. Acessed on 02 December 2017, 2002.
48. MOHSAC. *China, peoples Republic of China's maximum levels of contaminants in foods*; GAIN Report No. CH6064. USDA Foreign Agricultural Service: Beijing, China. 11., 2006.
49. Mokhtar, M.B., Aris, A.Z., Munusamy, V., Praveena, S.M. (2009). Assessment level of heavy metals in *Penaeus monodon* and *Oreochromis* spp. in selected aquaculture ponds of high densities development area. *European Journal of Scientific Research*, *30*(3), 348–360.
50. IAEA. *World-wide intercomparison exercise for the determination of trace elements and methylmercury in fsh homogenate international atomic energy agency 407 report no IAEA/ AL/144IAEA/ MEL/72*; 2003.
51. FAO. *Heavy metals regulations* Legal Notice No. 66/2003. http://extwprlegs1.fao.org/docs/pdf/eri42405.pdf. Accessed 08 June 2017, 2003.
52. Islam, R., Faysal, S.M., Amin, R., Juliana, F.M., Islam, M.J., Alam, J., Hossain, M.N., Asaduzzaman, M. (2017). Assessment of pH and total dissolved substances (TDS) in the commercially available bottled drinking water. *IOSR Journal of Nursing and health Science*, *6*(5), 35–40.
53. Omarjee, A., Taljaard, S., Ramjukadh, C.-L., van Niekerk, L. (2021). pH variability in catchment flows to estuaries – A South African perspective. *Estuarine, Coastal and Shelf Science*, *262*107605. https://doi.org/10.1016/j.ecss.2021.107605
54. USEPA. *Water: Monitoring and sssessment. Conductivity. https://archive.epa.gov/water/archive/web/html/vms59.html#:~:text=Studies%20of%20inland%20fresh%20waters,high%20as%2010%2C000%20%C2%B5mhos/cm. Accessed on the 19th March 2025*; 2025.
55. Rameshkumar, S., Radhakrishnan, K., Aanand, S., Rajaram, R. (2019). Influence of physicochemical water quality on aquatic macrophyte diversity in seasonal wetlands. *Applied water science*, *9,* 1–8.
56. Barbieri, M. (2016). The importance of enrichment factor (EF) and geoaccumulation index (Igeo) to evaluate the soil contamination. *Journal of Geology & Geophysics*, *5*(1), 1–4.
57. Weissmannová, H.D., Pavlovský, J. (2017). Indices of soil contamination by heavy metals-methodology of calculation for pollution assessment (minireview). *Environmental Monitoring and Assessment*, *189*(12), 616. https://doi.org/10.1007/s10661-017-6340-5
58. Liao, J., Cui, X., Feng, H., Yan, S. (2022). Environmental background values and ecological risk assessment of heavy metals in watershed sediments: A comparison of assessment methods. *Water*, *14*(1), 14010051. https://doi.org/10.3390/w14010051
59. Zheng, X., Rehman, A., Zhong, S., Faisal, S., Hussain, M.M., Fatima, S.U., Du, D. (2024). Source and ecological risk assessment of potentially toxic metals in urban riverine sediments using multivariate analytical and statistical tools. *Land*, *14*(1), 32. https://doi.org/10.3390/land14010032
60. Kolawole Tesleem, O., Olatunji Akinade, S., Jimoh Mustapha, T., Fajemila Olugbenga, T. (2018). Heavy metal contamination and ecological risk assessment in soils and sediments of an industrial area in Southwestern Nigeria. *Journal of Health and Pollution*, *8*(19), 180906. https://doi.org/10.5696/2156-9614-8.19.180906
61. Rzetala, M.A. (2015). Assessment of toxic metal contamination of bottom sediments in water bodies in urban areas. *Soil and Sediment Contamination: An International Journal*, *24*(1), 49–63.
62. Khan, K., Zeb, M., Younas, M., Sharif, H.M.A., Yaseen, M., Al-Sehemi, A.G., Kavil, Y.N., Shah, N.S., Cao, X., Maryam, A., Qasim, M. (2023). Heavy metals in five commonly consumed fish species from River Swat, Pakistan, and their implications for human health using multiple risk assessment approaches. *Marine Pollution Bulletin*, *195,* 115460. https://doi.org/10.1016/j.marpolbul.2023.115460
63. Yi, Y., Zhang, S. (2012). The relationships between fish heavy metal concentrations and fish size in the upper and middle reach of Yangtze River. *Procedia Environmental Sciences*, *13,* 1699–1707.
64. Jooste, A., Marr, S., Addo-Bediako, A., Luus-Powell, W. (2015). Sharptooth catfish shows its metal: a case study of metal contamination at two impoundments in the Olifants River, Limpopo River system, South Africa. *Ecotoxicology and Environmental Safety*, *112,* 96–104. https://doi.org/10.1016/j.ecoenv.2014.10.033
65. Addo-Bediako, A., Marr, S.M., Jooste, A., Luus-Powell, W.J. (2014). Are metals in the muscle tissue of Mozambique tilapia a threat to human health? A case study of two impoundments in the Olifants River, Limpopo province, South Africa. *International Journal of Limnology*, *50*(3), 201–210. http://dx.doi.org/10.1051/limn/2014091
66. Lynch, A.J., Cooke, S.J., Deines, A.M., Bower, S.D., Bunnell, D.B., Cowx, I.G., Nguyen, V.M., Nohner, J., Phouthavong, K., Riley, B. (2016a). The social, economic, and environmental importance of inland fish and fisheries. *Environmental Reviews*, *24*(2), 115–121.

67. Mannzhi, M.P., Edokpayi, J.N., Durowoju, O.S., Gumbo, J., Odiyo, J.O. (2021). Assessment of selected trace metals in fish feeds, pond water and edible muscles of Oreochromis mossambicus and the evaluation of human health risk associated with its consumption in Vhembe district of Limpopo Province, South Africa. *Toxicology Reports*, *8,* 705–717. https://doi.org/10.1016/j.toxrep.2021.03.018
68. WHO (2005). *List of Maximum Levels of Heavy Metals Recommended for Fish by the Joint FOA/WHO Codex Alimentarius Commission, 2nd edition*, 2003, 1–8. Rome. Italy.
69. Ahmed, M.K., Baki, M.A., Kundu, G.K., Islam, M.S., Islam, M.M., Hossain, M.M. (2016). Human health risks from heavy metals in fish of Buriganga river, Bangladesh. *SpringerPlus*, *5*(1), 1697–1709. https://doi.org/10.1186/s40064-016-3357-0
70. Nibamureke, U., Barnhoorn, I., Wagenaar, G. (2016). Health assessment of freshwater fish species from Albasini Dam, outside a DDT-sprayed area in Limpopo province, South Africa: a preliminary study. *African Journal of Aquatic Science*, *41*(3), 297–308.
71. Lynch, L., Jirsa, F., Avenant-Oldewage, A. (2016b). Trace element accumulation and human health risk assessment of *Labeo capensis* (Smith, 1841) from the Vaal Dam reservoir, South Africa. *Water SA*, *42*(2), 328–336.
72. Nzeve, J.K., Kitur, E. (2019). Bioaccumulation of heavy metals in Common carp (*Cyprinus carpio*) of Masinga Dam, Kenya.
73. MHSAC. *China, Peoples Republic of FAIRS Product Specific Maximum Levels of Contaminants in Foods*; GAIN Report Number: CH6064. Beijing, China, 2006.
74. Naangmenyele, Z., Ncube, S., Akpabey, F.J., Dube, S., Nindi, M.M. (2021). Bioaccumulation and human risk assessment of heavy metals in *Oreochromis niloticus* and *Clarias gariepinus* fish species from the Golinga Reservoir, Ghana. *South African Journal of Chemistry*, *75*111–116.
75. Hossain, M.B., Ahmed, M.M., Jolly, Y.N., Nur, A.U., Sultana, S., Akter, S., Yu, J., Paray, B.A., Arai, T. (2023). Potential Toxic Elements and Their Carcinogenic and Non-Carcinogenic Risk Assessment in Some Commercially Important Fish Species from a Ramsar Site. *Biology (Basel)*, *12*(8), https://doi.org/10.3390/biology12081072
76. Kotacho, A.A., Yimer, G.T., Sota, S.S., Berego, Y.S. (2024). Level of heavy metals in fish and associated human health risk from the Omo Delta in Southern Ethiopia: A first-hand report. *Environ Health Insights*, *18,* 11786302241238180. https://doi.org/10.1177/11786302241238180
77. Yin, J., Cheng, L., Jiang, X., Wang, L., Gao, P., Zhong, W., Zhang, X. (2024). Metals levels and human health risk assessment in eight commercial fish species collected from a market, Wuhan, China. *Frontiers in Sustainable Food Systems*, *8.* https://doi.org/10.3389/fsufs.2024.1346389
78. Blankson, E.R., Ohene-Obeng, N.K.A., Awuah, B.A., Oduro, D., Ewool, J., Gbogbo, F. (2024). Heavy metal bioaccumulation in highly consumed pelagic and benthic fish and associated health risk. *Biological Trace Element Research*, *202*(8), 3781–3788. https://doi.org/10.1007/s12011-023-03943-2
79. Barone, G., Storelli, A., Meleleo, D., Dambrosio, A., Garofalo, R., Busco, A., Storelli, M.M. (2021). Levels of mercury, methylmercury and selenium in fish: insights into children food safety. *Toxics*, *9*(2), 39. https://doi.org/10.3390/toxics9020039
80. Li, X., Meng, Z., Bao, L., Su, H., Wei, Y., Liu, X., Wang, F., Ji, N., Zhang, R. (2024). Occurrence, bioaccumulation, and risk evaluation of selenium in typical Chinese aquatic ecosystems. *Journal of Cleaner Production*, *435*140552.
81. McPherson, C.A., Lawrence, G.S., Elphick, J.R., Chapman, P.M. (2014). Development of a strontium chronic effects benchmark for aquatic life in freshwater. *Environmental Toxicology and Chemistry*, *33*(11), 2472–2478. 10.1002/etc.2696
82. Lebepe, J., Oberholster, P.J., Ncube, I., Smit, W., Luus-Powell, W.J. (2020). Metal levels in two fish species from a waterbody impacted by metallurgic industries and acid mine drainage from coal mining in South Africa. *Journal of Environmental Science and Health, Part A*, *55*(4), 421–432. https://doi.org/10.1080/10934529.2019.1704604
83. Monferran, M.V., Garnero, P.L., Wunderlin, D.A., de los Angeles Bistoni, M. (2016). Potential human health risks from metals and As via Odontesthes bonariensis consumption and ecological risk assessments in a eutrophic lake. *Ecotoxicology and Environmental Safety*, *129,* 302–310.
84. Maurya, P.K., Malik, D.S. (2018). Bioaccumulation of heavy metals in tissues of selected fish species from Ganga river, India, and risk assessment for human health. *Human and Ecological Risk Assessment: An International Journal*, 1–19. https://doi.org/10.1080/10807039.2018.1456897
85. Sara, J.R., Marr, S.M., Smit, W.J., Erasmus, L.J.C., Luus-Powell, W.J. (2017). Human health risks of metals and metalloids in muscle tissue of *Synodontis zambezensis* Peters, 1852 from Flag Boshielo Dam, South Africa. *African Journal of Aquatic Science*, *42*(3), 287–291. https://doi.org/10.2989/16085914.2017.1361378
86. Huang, X., Qin, D., Gao, L., Hao, Q., Chen, Z., Wang, P., Tang, S., Wu, S., Jiang, H., Qiu, W. (2019). Distribution, contents and health risk assessment of heavy metal(loid)s in fish from different water bodies in Northeast China. *RSC Advances*, *9*(57), 33130–33139. http://dx.doi.org/10.1039/C9RA05227E

87. Biswas, A., Kanon, K.F., Rahman, M.A., Alam, M.S., Ghosh, S., Farid, M.A. (2023). Assessment of human health hazard associated with heavy metal accumulation in popular freshwater, coastal and marine fishes from south-west region, Bangladesh. *Heliyon*, *9*(10), https://doi.org/10.1016/j.heliyon.2023.e20514
88. Ezemonye, L.I., Adebayo, P.O., Enuneku, A.A., Tongo, I., Ogbomida, E. (2019). Potential health risk consequences of heavy metal concentrations in surface water, shrimp (*Macrobrachium macrobrachion*) and fish (*Brycinus longipinnis*) from Benin River, Nigeria. *Toxicology Reports*, *6,* 1–9. https://doi.org/10.1016/j.toxrep.2018.11.010
89. Esilaba, F., Moturi, W.N., Mokua, M., Mwanyika, T. (2020). Human health risk assessment of trace metals in the commonly consumed fish species in Nakuru Town, Kenya. *Environmental Health Insights*, *14,* 1178630220917128. https://doi.org/10.1177/1178630220917128
90. Vu, C.T., Lin, C., Yeh, G., Villanueva, M.C. (2017). Bioaccumulation and potential sources of heavy metal contamination in fish species in Taiwan: assessment and possible human health implications. *Environmental Science and Pollution Research*, *24*(23), 19422–19434. https://doi.org/10.1007/s11356-017-9590-4
91. Noman, M.A., Feng, W., Zhu, G., Hossain, M.B., Chen, Y., Zhang, H., Sun, J. (2022). Bioaccumulation and potential human health risks of metals in commercially important fishes and shellfishes from Hangzhou Bay, China. *Scientific Reports*, *12*(1), 4634. https://doi.org/10.1038/s41598-022-08471-y
92. Roy, D., Islam, S.S., Quraishi, S.B., Hosen, M.M., Rahman, F., Samad, A., Latifa, G.A. (2021). Comprehensive analysis of toxic metals and their sources accumulated by cultured Oreochromis niloticus in Pagla Sewage Treatment Plant, Narayanganj, Dhaka, Bangladesh. *Arabian Journal of Geosciences*, *14*(16), 1556. https://doi.org/10.1007/s12517-021-07917-3
93. Islam, M.S., Ahmed, M.K., Habibullah-Al-Mamun, M. (2015b). Determination of heavy metals in fish and vegetables in Bangladesh and health implications. *Human and Ecological Risk Assessment: An International Journal*, *21*(4), 986–1006. https://doi.org/10.1016/j.etap.2014.12.009